Georgia Tech Sponsored Research

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Project	E-20-M97	
Project director	Leon	Roberto
Research unit	CEE	
Title	Three-Dimensional Slab Effects in Partially-Restrained Composite Connections	
Project date	9/30/2000	

E-20-M97
#2

Final Report for Period: 07/1997 - 06/2000 **Submitted on:** 10/03/2000

Principal Investigator: Leon, Roberto T. **Award ID:** 9710238

Organization: GA Tech Res Corp - GIT

Three-Dimensional Slab Effects in Partially-Restrained Composite Connections

Project Participants

Senior Personnel

Name: Leon, Roberto
Worked for more than 160 Hours: Yes
Contribution to Project:

Name: White, Donald
Worked for more than 160 Hours: Yes
Contribution to Project:

Post-doc

Graduate Student

Name: Maleck, Andrea
Worked for more than 160 Hours: No
Contribution to Project:
Ph.D. student working on design aspects of the problem under study.

Name: Alemdar, Bulent
Worked for more than 160 Hours: Yes
Contribution to Project:
Ph.D. student in charge of modelling aspects of the problem

Name: Green, Travis
Worked for more than 160 Hours: Yes
Contribution to Project:
M.S. student in charge of experimental portion of the work.

Name: Taylor, Joshua
Worked for more than 160 Hours: Yes
Contribution to Project:
M.S. student in charge of development of connection model

Name: Park, Joonam
Worked for more than 160 Hours: Yes
Contribution to Project:
M.S. student in charge of developing visualization software.

Name: Smallidge, Jeff
Worked for more than 160 Hours: Yes
Contribution to Project:
M.S. student in charge of initial experimental planning

Undergraduate Student

Name: Lyons, Frank
Worked for more than 160 Hours: No
Contribution to Project:
Helped in laboratory studies

Name: Aviles-Amador, Diego
Worked for more than 160 Hours: Yes
Contribution to Project:
Helped in laboraory setup and testing

Name: Perez, Armando
Worked for more than 160 Hours: Yes
Contribution to Project:
Helped setup test in the laboratory.

Name: Allen, Rhonda
Worked for more than 160 Hours: No
Contribution to Project:
Worked in laboratory helping in setting up test.

Organizational Partners

Cives Steel Corporation
Donated and fabricated steel pieces for test.

Other Collaborators or Contacts

Stanley D. Lindsey and Associates, Structural Engineers, Atlanta, GA, provided technical help. Dr. Clint Rex was particularly helpful.

The Department of Civil Engineering, University of Trieste (Italy) provided analytical and modeling support. Mr. Gian Andrea Rassati, a doctoral candidate at Trieste, spent 6 months in Atlanta as part of this collaboration.

Activities and Findings

Project Activities and Findings: (See PDF version submitted by PI at the end of the report)
Project Training and Development: (See PDF version submitted by PI at the end of the report)
Research Training:
This project gave the opportunity to several graduate and undergraduate students to pursue advanced research in structural engineering. Much of the effort of the advanced graduate students was focused on developing sophisticated modeling and analysis tools using the latest C++ routines, database management techniques, and visualization tools. This gave them an opportunity to explore some unique, challenging problems and to strengthen their understanding of fundamental mechanics, material modeling, numerical stability and convergence issues, and computer programming.

Two of the M.S. students and three undergraduate students focused their efforts on development of a testing setup, instrumentation, data acquisition, and testing of a very large three-dimensional specimen. The sheer scale of the test was exciting and led to protracted discussions of experimental techniques, scale effects, servo-hydraulics, and data acquisition issues. The experimental program also gave the students great insight into the real behavior of structures. The three undergraduates that worked in the latter part of this program have or will continue on to graduate studies.

Outreach Activities:

Journal Publications

Alemdar, B.N., Green, T.P., White, D.W. and Leon, R.T., "Three-Dimensional Slab Effects in Partially-Restrained Composite Construction",

Composite Construction in Steel and Concrete IV, ASCE, New York, N.Y., 11 pp., p. , vol. , (2000).) Submitted

Books or Other One-time Publications

Alemdar, B.N., Taylor, J., White, D.W. and Leon, R.T., "Nonlinear Analysis of Buildings with PRC Connections", (1999). *Book*, Published
Editor(s): R. Avent and M. Alawady
Collection: Structural Engineering in the 21st Century, Proceedings of the 1999 ASCE Structures Congress
Bibliography: ASCE, Reston, VA, pp. 402-405

White, D.W., Alemdar, B.N., Taylor, J.M., Leon, R.T. and Green, T.P., "Nonlinear Analysis of PRC Frames Using Partial-Composite Beam Elements and Component-Based Connection Models", (2000). *Book*, Published
Editor(s): Y. Xiao and S. A. Mahin
Collection: Proceedings of the 6th ASCCS Conference on Composite and Hybrid Structures, Los Angeles, March 22-24, 2000
Bibliography: Vol. 2, ASCCS,University of Southern California, Los Angeles, CA, pp. 1075-1082

Green, Travis P., "Behavior of Full-Scale Partially-Restrained Composite Beam-to-Column T-Stub and Shear Tab Connections Under Cyclic Loading", (2000). *Thesis*, Published
Bibliography: M.S. Thesis, Georgia Institute of Technology, Atlanta, GA

Rassati, G.A., Leon, R.T. and Noe, S., "PR Composite Connections: A Component Modelling Approach", (2001). *Book*, Accepted
Editor(s): R.T. Leon and W.S. Easterling
Collection: Proceedings of the Fourth International Workshop on Connections in Steel Structures, Roanoke, VA, Oct. 20-25, 2000
Bibliography: AISC, Chicago.

Maleck, A.E. and White, D.W., "Behavior and Design of Partially-Restrained Composite Framing Systems", (2000). *Book*, Accepted
Editor(s): F. Wald and C. Daniotapoulus
Collection: The Paramount Role of Joints into the Reliable Response of Structures: From the Rigid and Pinned Joints to the Notion of Semi-rigidity
Bibliography: NATO Advanced Research Workshop, Ouranoupolis, Greece, May 21-23, 2000, 14 pp.

Maleck, A.E. and White, D.W., "Analysis and Design Methods for Partially-Restrained Steel Framing Systems", (2000). *Book*, Accepted
Collection: Proceedings of the Annual SSRC Technical Session, Memphis, July 24-26, 2000
Bibliography: Structural Stability Research Council, Gainsville, FL, 14. pp.

Taylor, J.M., "Nonlinear Analysis of Steel Frames with Partially-Restrained Composite Connections and Full or Partially-Composite Girders", (1999). *Thesis*, Published
Bibliography: M.S. thesis, Georgia Institute of Technology, Atlanta, GA

Park, Joonam, "A Visualization System for Nonlinear Frame Analysis", (1999). *Book*, Published
Bibliography: M.S. thesis, Georgia Institute of Technology, Atlanta, GA

Alemdar, B.N., "Inelastic Analysis of Steel Building Structural Systems", (2001). *Book*, In progress
Bibliography: Ph.D. dissertation, Georgia Institute of Technology, Atlanta, GA

Maleck, A.E, "Design and Analysis of Partially-Restrained Composite Steel Framing Systems", (2001). *Thesis*, In progress
Bibliography: Ph.D. dissertation, Georgia Institute of Technology, Atlanta, GA

Web/Internet Sites

URL(s):

Description:

Other Specific Products

Contributions

Contributions within Discipline:
This project has contributed significantly to structural engineering by:

a) Developing a framework for incoporating all major phenomena associated with composite steel frame behavior (non-linear connection behavior, cyclic laoding, partial interaction, slab effects, second-order stability, and 3D considerations) into a single, comprehensive model for frame analysis and design.

b) Implementing the framework into an advanced computer code, including visualization tools that permit an accurate assessment of the contributions of different mechanisms to the deformation of the frame.

c) Reporting on a unique, 3D test on a full-scale building connection that includes a large enough slab to permit accurate reproduction of real structral behavior.

Contributions to Other Disciplines:

Contributions to Human Resource Development:
Two doctoral students, four M.S. students, and four undergraduates have been supported partially/fully through this research project. Most importantly, through the leveraging of REU funds, three minority undergradutes were involved in the project's experimental phase. All three of them are continuing on to graduate school at prestigious universities.

Contributions to Science and Technology Infrastructure:

Beyond Science and Engineering:

Categories for which nothing is reported:

Activities and Findings: Any Outreach Activities
Any Product
Contributions: To Any Other Disciplines
Contributions: To Any Science or Technology Infrastructure
Contributions: Beyond Science or Engineering

The project was divided into two main parts. The first was the development of analysis tools to model the behavior of composite PR connections. This included both development of connection and member models as well as of visualization tools. The second was the testing of a full-scale interior connection.

Analytical Studies

The analytical component of this research focused on new elements capable of efficiently modeling composite action under cyclic load reversals. The analysis models being developed are targeted at inelastic static and time-history analysis of large three-dimensional building structural systems with PR-C connections. The targeted computing platforms are mid- to high-end desktop computers. The following approaches have been developed to achieve this capability:

Beam Modeling: The floor girders are modeled using beam-type kinematics. Both fully-composite and partially-composite interaction are addressed. In the case of partially-composite interaction, the interface slip between the steel girder and the composite decking is modeled explicitly within the beam element formulation. These beam elements are force based. The fully-composite beam element is taken largely after Spacone (1996) and Neuenhofer and Fillipou (1997), and the partially-composite beam element is based largely on the prior research by Salari et al. (1998). These elements offer significant advantages in coarse-element accuracy over conventional displacement-based finite element models, due to the fact that the force fields on which they are based satisfy the governing differential equations of equilibrium at the section level along the length of the member. A continuous load-slip relationship is used to model the partial shear interaction in the latter of the two elements. Also, the fully-composite beam element utilizes a stress-resultant moment-curvature constitutive model, whereas the partially-composite element is based on a fiber idealization of the slab and beam cross-sections. The modeling of the slab in these elements is based on an effective width idealization, which may be varied along the beam length.

Connection Modeling: The behavior in the vicinity of the beam-to-column connection is modeled using a component-based approach. That is, the force-deformation behavior of each of the structural components that provide the force transfer between the floor system and the steel column is modeled directly, and the different force-deformation models are combined to represent the complete behavior associated with this force transfer. This model may be used to obtain a basic connection moment-rotation (M-■) curve for use with the full-composite beam element, or alternately, the M-■ curve may be specified directly for use with this element. However, for the partially-composite beam element, the connection component model and the beam and beam-column models are combined as illustrated in Fig. 1. This figure represents the idealization within the strong-axis plane of Fig. 4 (specimen used in the experimental part of the work) , with the use of T-stubs on both sides of the joint. The model of the slab within the connection region is composed of two fundamental types of spring elements: load introduction and load redirection springs. These springs are targeted at representation of the force transfer mechanism illustrated in Fig. 2 for a PR-C connection under negative or sidesway moments. The load introduction spring models the slab force transfer in tension to the opposite side of the column, whereas the load redirection spring models the transfer of the slab force to the column through bearing. The basic layout of the model shown in Fig. 1 is the same as that developed by Tschemmernegg et al. (1994), except that the slip resistance between the steel beam and the slab is modeled directly within the beam element in this work, as opposed to the use of a discrete slip spring component in Tschemmernegg's research.

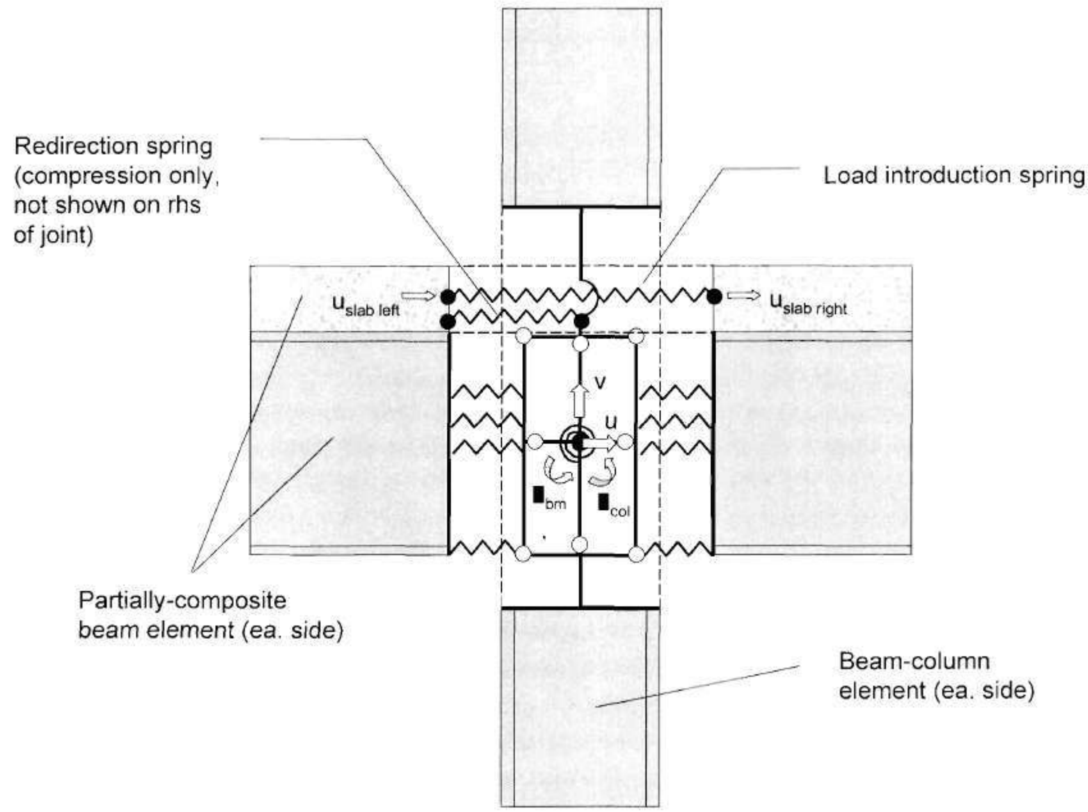

Figure 1. Spring model of an interior PR-C joint in the strong direction.

A detailed component representation of a T-stub connection to the bottom flange is outlined in Fig. 3. In Fig. 1, this connection is represented by the single spring between the column face and the bottom flange of the beam. In general, this spring can be broken down into a sub-group of spring components, connected in series, which account for the following deformations: (1) column web transverse deformation due to the load introduction from the T, (2) axial deformation of the tension bolts (acting as springs in parallel), (3) bending deformations of the T-stub flange and the column flange, (4) axial straining of the T-stem, (5) displacement within the shear connection, including slip and bearing deformations, and (6) localized (non-planar) deformations in the beam flange and web due to the transfer of force from the T stem. A similar idealization is used for the web angles, which are illustrated by the springs between the beam webs and the column flanges in Fig. 3.

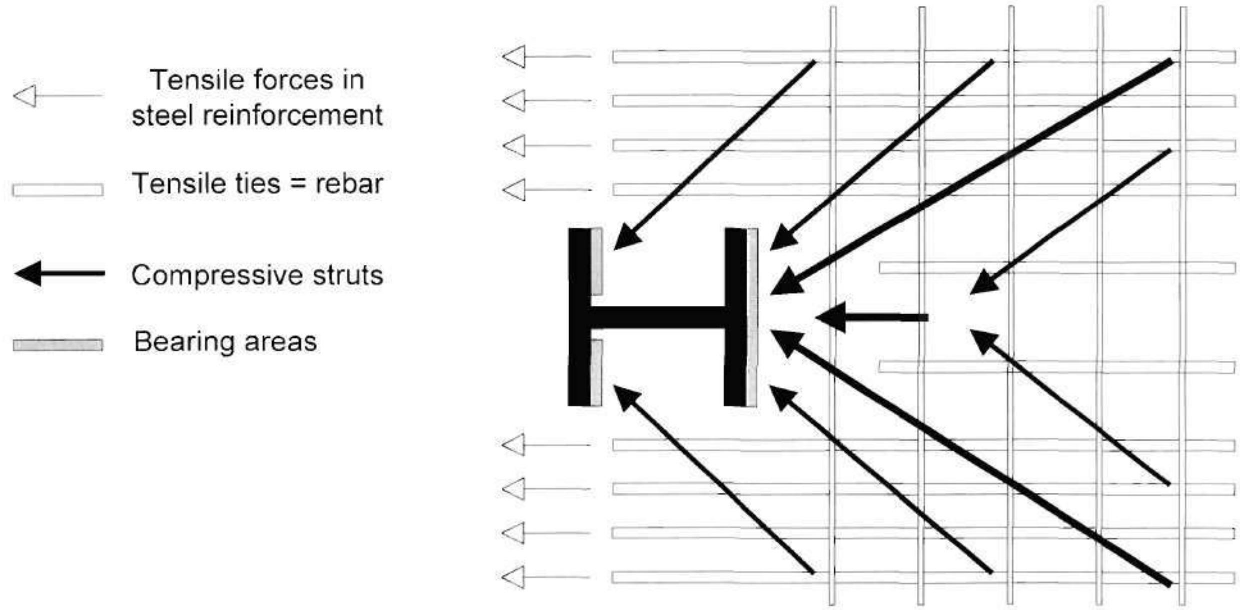

Figure 2. Slab force transfer mechanism for PR-C connections under negative or sidesway moments.

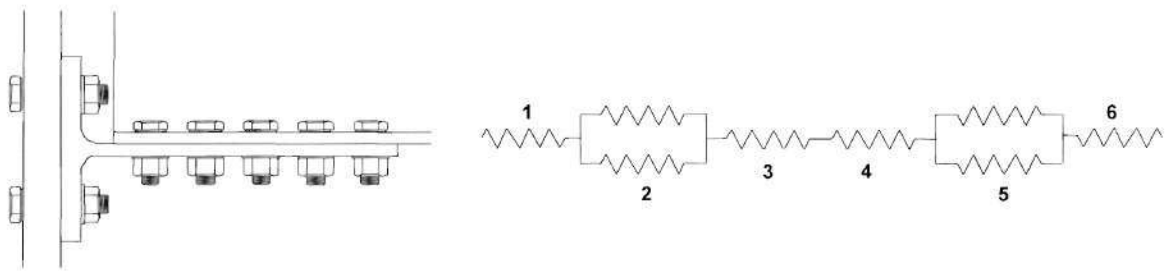

Figure 3. Component representation of a T-stub connection.

Panel Zone Modeling: The finite size and deformability of the column panel zone for strong-axis connections is modeled using a shear-panel constraint (see Fig. 1). This constraint idealizes the deformation of the panel zone as a single uniform shear-racking distortion. The rotations within the plane of strong-axis bending at the column faces on each side of the panel are constrained to be equal, and the in-plane rotations at the top and bottom of the panel, at the connection to the beam-column elements are equal, but different than the column face rotations.

Idealization of floor diaphragms for three-dimensional analysis: The floor diaphragms are assumed to be rigid for the purpose of modeling the overall system behavior. That is, the column displacements within the plane of a floor are described by two translations and a rotation about a normal to the plane of the floor. However, the floor girder-slab system is modeled based on the assumption that the total axial force at any girder section, including an effective portion of the slab, is equal to zero. Once the three-dimensional rigid-body displacements are factored out, the composite beams are simply two-dimensional elements. That is, the beam deformations are only two-dimensional, but the beam-slab elements are participating as components within the overall three-dimensional structural system. For the case of the partial-composite beam element, this kinematic model for the beams requires a non-standard floor-diaphragm constraint. The neutral axis of the beam elements is independent of the location of the rigid diaphragm, and thus the beams are allowed to "breathe axially" relative to the rigid diaphragm while providing rotational restraint to the columns about their axis of bending.

Hysteretic models: For partial-composite beams, the slip force-slip displacement relationship is modeled by a cyclic inelastic model. The cyclic load-slip behavior is expected to be similar to that obtained experimentally by Gattesco & Giuriani (1996). The hysteretic behavior of the various components is represented by a suite of models, which include the following attributes: (1) unsymmetric behavior in tension & compression of some steel components (due to stability effects), (2) stable symmetric hysteretic behavior of certain steel components, (3) abrupt stiffening of the force-deformation curve due to contact between components, e.g., contact in compression between the T-stub flange and the column flange in modeling the effects of bending in these components, (4) slip within shear connections, (5) stiffness and strength degradation and pinching behavior in the slab concrete response.

Beam-column model: The steel columns are modeled by a second-order three-dimensional beam-column finite element that is capable of tracking inelastic torsional-flexural actions, including cross-section warping. This element has been completed in recent research (Nukala and White, 1998a and b). It has 14 global degrees of freedom, three translation and three rotation dofs at each end, and two warping dofs at each end. This element has a mixed formulation to allow it to achieve good accuracy for general inelastic analysis.

Software platform: The above tools have been implemented within the FE++ object-oriented programming framework, originally developed by Lu et al. (1994). A flexible graphical user interface is being developed to allow the engineer to be able to rapidly investigate and interpret any of the detailed responses produced by the analysis at the level of the various structural components (i.e., contours, diagrams and plots of responses), as well as synthesized performance indices of the overall structural behavior (e.g., animation of the sequence of formation of plastic hinges within the structure for a given earthquake excitation, or envelopes of the maximum ductility demands throughout the structure for a set of earthquake acceleration histories).

Experimental Testing

One full-scale PR composite - interior joint was tested. The connection was fabricated with T-stubs on the bottom flange s in the strong direction and with web shear plates in the weak direction (Fig. 1).

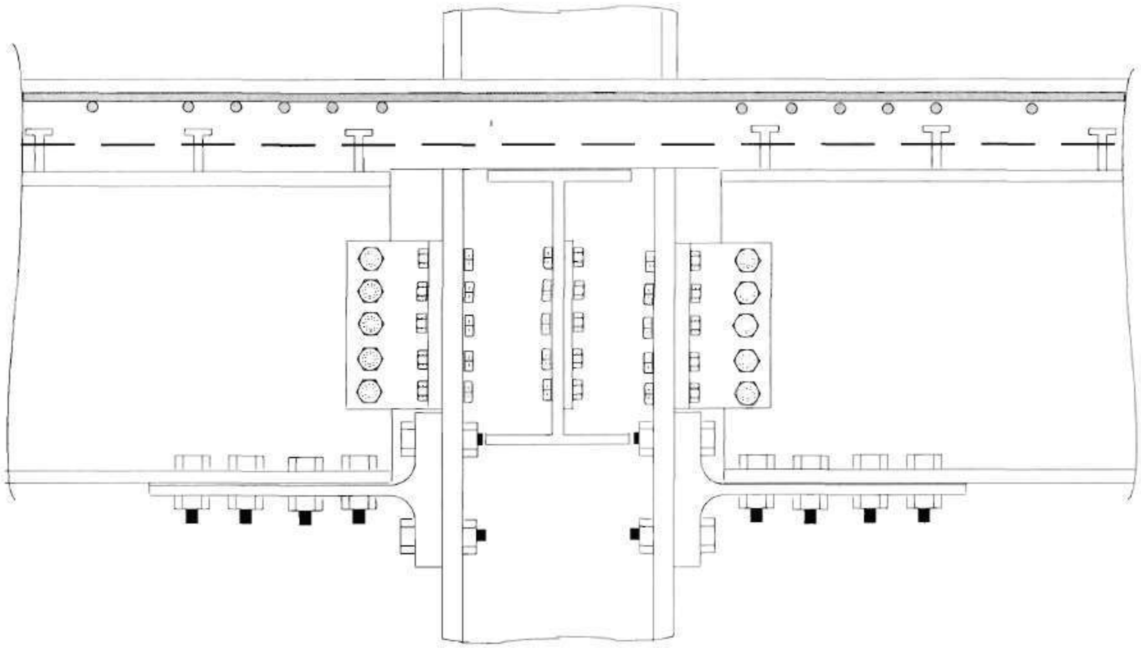

Figure 4. View of interior PR composite connection tested.

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Tschemmernegg, F., Brugger, R. Hittenberter, R, Wiesholzer, J., Huter, M, Schaur, B.C., and Badran, M.Z. (1994). "Zur Nachgiebigkeit von Verbundknoten," *Stahlbau*, 63, 3-19.

EXPERIMENTAL FINDINGS

As part of this project a full-scale, bi-directional, partially-restrained (PR) composite beam-to-column connection specimen was tested.. The test specimen had a 22' x 30', 3-1/4" lightweight concrete slab on 3" VLI 20 composite decking. Simply supported (SS) W24x55 girders framed into the weak axis of a W14x159 column while PR W18x40 beams framed into the strong axis. The PR connection consisted of continuous reinforcement bars across the column and a T-stub bolted onto each bottom beam flange. The SS connection consisted of continuous reinforcement bars across the column and a shear tab. The bi-directional configuration, bi-directional and repetitive cyclic loading and lightweight concrete slab makes this test unique. The specimen was subjected to repetitive cyclic load reversals following the SAC testing protocol.

Overall connection behavior was significantly influenced by failure of the concrete slab, yielding of the column panel zone, transverse punching of the column web and bare steel connection detailing. The connection remained approximately elastic up to 1.0% drift. During this time, the connection maintained good strength and stiffness. After 1.0% drift, the connection went into the inelastic range where pinching behavior, both with respect to load versus tip displacement and moment versus concentrated rotation, was apparent. Soon after the 2% drift limit was exceeded, crushing of the concrete against the column flanges was noted. The effective slab width at this level was roughly equal to eight column flange widths. At 3% drift extensive yielding in the panel zone and some yielding in the beams was noted (Fig.1). At this drift the concrete began to fail in bearing leading to a progressive deterioration of the slab around the column (Fig. 2), and the behavior of the specimen began to degrade to that of the steel specimen alone. An interesting failure phenomenon, the punching of the shear tabs through the column web and fracture of the shear tab welds, was observed in the weak direction.

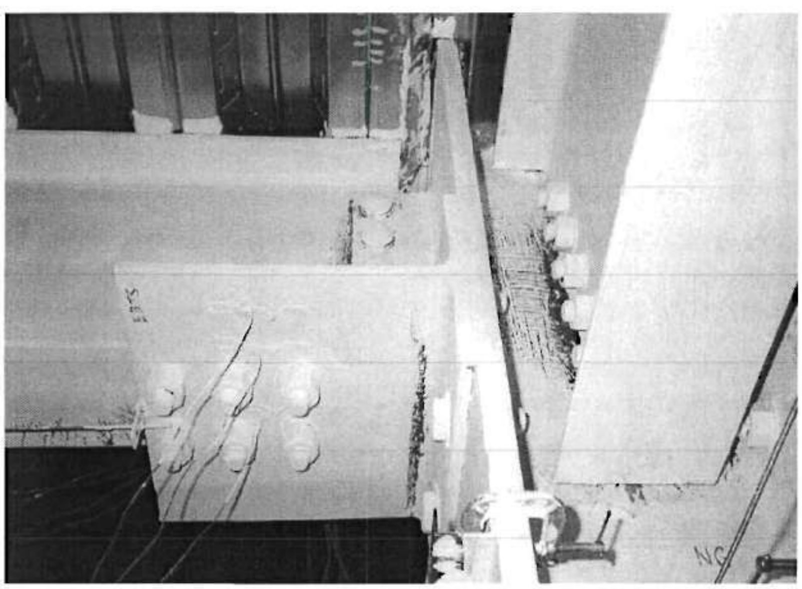


Figure 1 – View of yielding in the connection area at 3% drift.

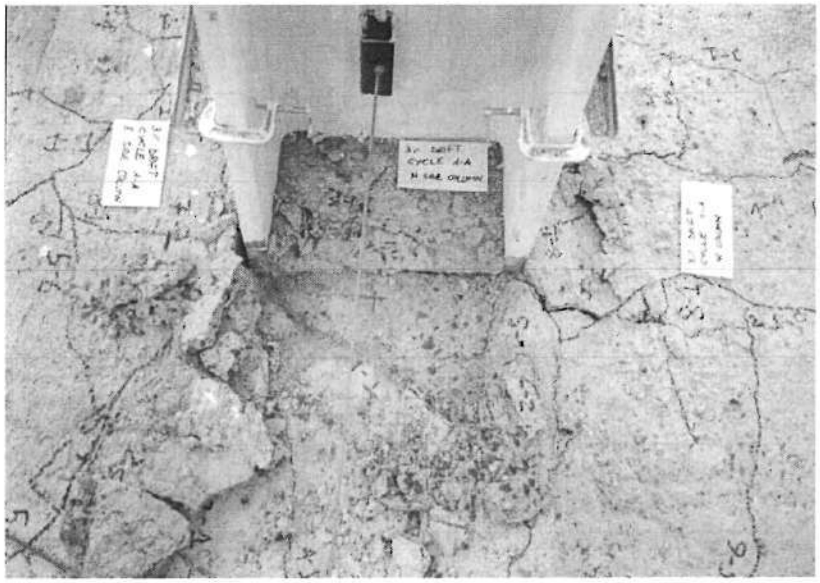


Figure 2 – Crushing of the concrete around the column at 3% drift.

MODELING AND ANALYSIS FINDINGS

The component-based connection models developed in this research, combined with (a) a new approach for simple idealization of the slab within the vicinity of beam-to-column connections, and (b) a flexibility-based partial-composite beam finite element, are capable of simulating the load-transfer mechanisms at the joints of partially-restrained composite subassemblies having a wide range of different attributes and characteristics. These models can be used as a research tool to understand the sensitivity of the structural response to connection details, slab shear connection, etc.

The models developed have been calibrated against available experimental data, and have been shown to be numerically robust and capable of reproducing behavior at the local (or component) level. Thus the models can be used to study different yield and failure mechanisms, and are useful for conducting detailed parametric studies.

The models have been incorporated into the existing platform FE++, which will be soon available to other researchers.

Example frame

Figure 3 is an elevation view of a two bay frame with bay length of 25 ft. 8 in. and story height of 13 ft., tested by Ammerman (1988) at the University of Minnesota. The columns are W14x120, pinned at the top and bottom to model inflection points at mid-story height, and the beams are W14x38 with a 3 1/4 in. concrete composite slab on 2 in.

formed metal deck. The ribs of the metal deck are oriented perpendicular to the axis of the beam. A 6x6x3/8 in. tube connects the top of all three columns. A36 steel is utilized for the columns and the beams. The frame has a 60 in. wide solid lightweight concrete slab with a nominal strength of 3.5 ksi. Composite action is provided by a pair of headed shear connectors (2 ½ x 5/8 in.) placed at every 12 in. along the beam. Eight #4 longitudinal reinforcing bars with a yield strength of 63 ksi are placed at a spacing of 6 in. and they are continuous across all connections. The slab is extended 2 ft. beyond the centerline of the exterior column to provide anchorage for the slab reinforcement. The exterior portion of the slab is reinforced with one #4 transverse bar at the left exterior connection and with three #4 bars at the other exterior connection. Transverse reinforcement bars for the interior part are placed with a spacing of 2 ft. The beam-column connection consists of an L 7x4x3/8 seat angle, 8 in. wide, and 2L 4x4x1/4 double web angles, 11 in. long. Both the seat and web angles have a yield stress of 43 ksi. The connection details are shown in Fig. 4.

The gravity load is applied to the frame as two symmetrical point loads (P) as shown in Fig. 3. This load is increased to 15.8 kips and held constant while the frame is loaded horizontally by a displacement-controlled cyclic lateral load (H). The structure is cycled at interstory drifts of 0.1, 0.25, 0.5, 0.75, 1.00, 1.50, and 2.00 percent.

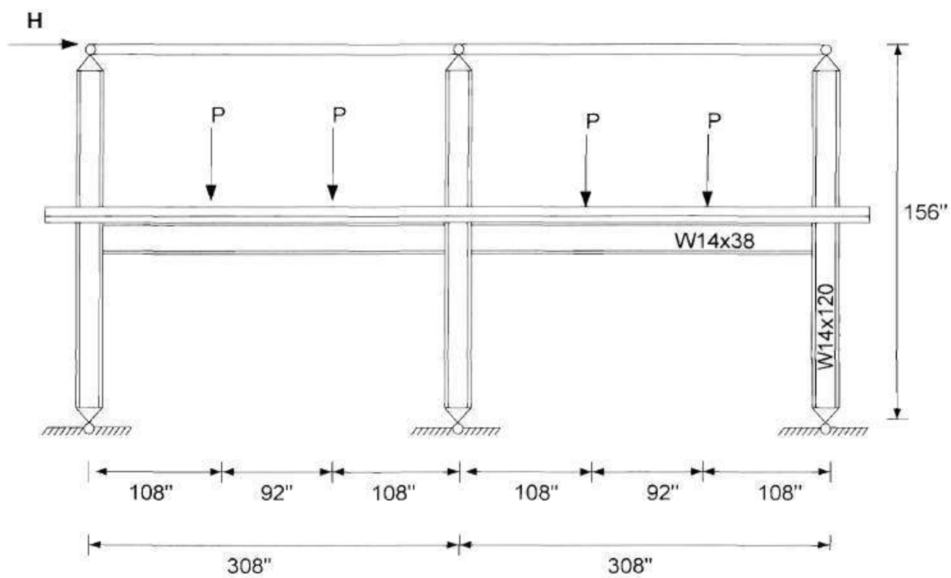


Figure 3. Test frame, tested by Ammerman (1988)

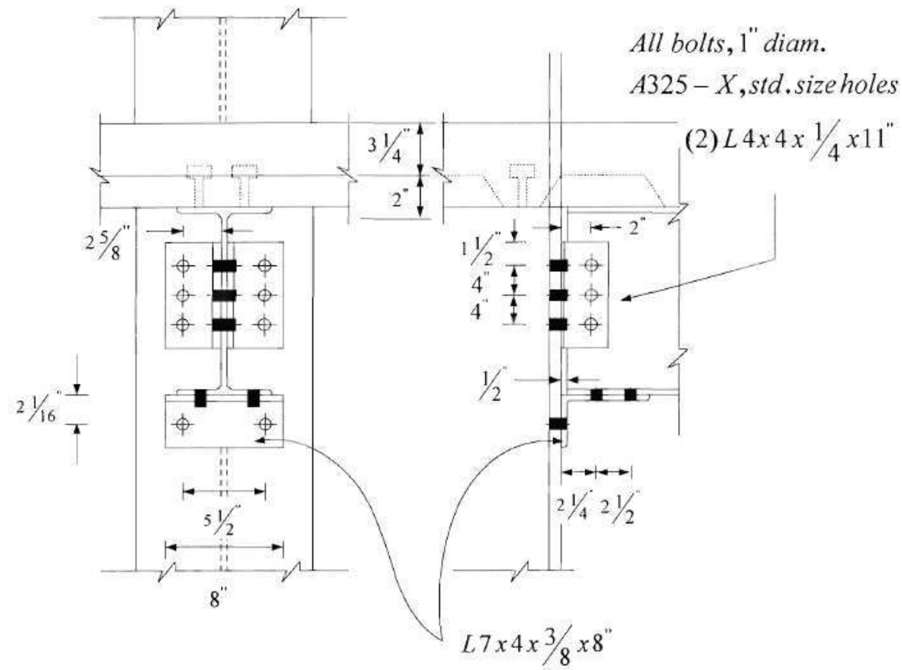


Figure 4. Connection detail, tested by Ammerman (1988)

Analysis approach

The predominant force transfer mechanism from the slab to the steel column at an interior PRC joint is illustrated in Fig. 5. In this figure, there is shown a negative bending moment on the left side and a positive bending moment on the right side of the column. This unbalanced moment is directed to the column mainly by compressive forces in the concrete slab with bearing against not only to the column exterior face but also into the column interior face. The bearing locations for a positive moment on the right side are highlighted by the thick solid lines drawn next to the column cross-section profile in the figure. Furthermore, tensile forces in the concrete slab are predominantly transferred from one side to the other side of the column by longitudinal reinforcing steel bars. Obviously, this force transfer mechanism shifts from one side of the column to the other when cyclic lateral loads are applied

In this research, the behavior around the beam-column joints is represented by a model that includes a tapered idealization of the slab in the vicinity of the beam-column joints (see Fig. 6.) The width of the slab is assumed equal to the column flange width at the column face and it extends outward from the column face at 45 degrees to the full slab width of 60 in. Furthermore, confinement in the concrete slab is varied along the beam in such a way that the increase in maximum compressive strength due to confinement is assumed to be a factor 1.3 at

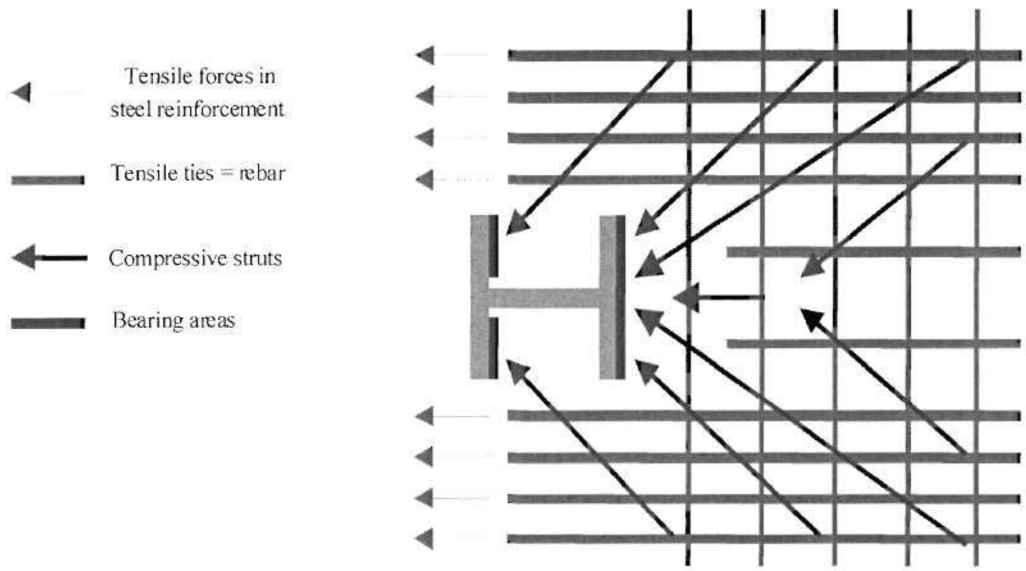
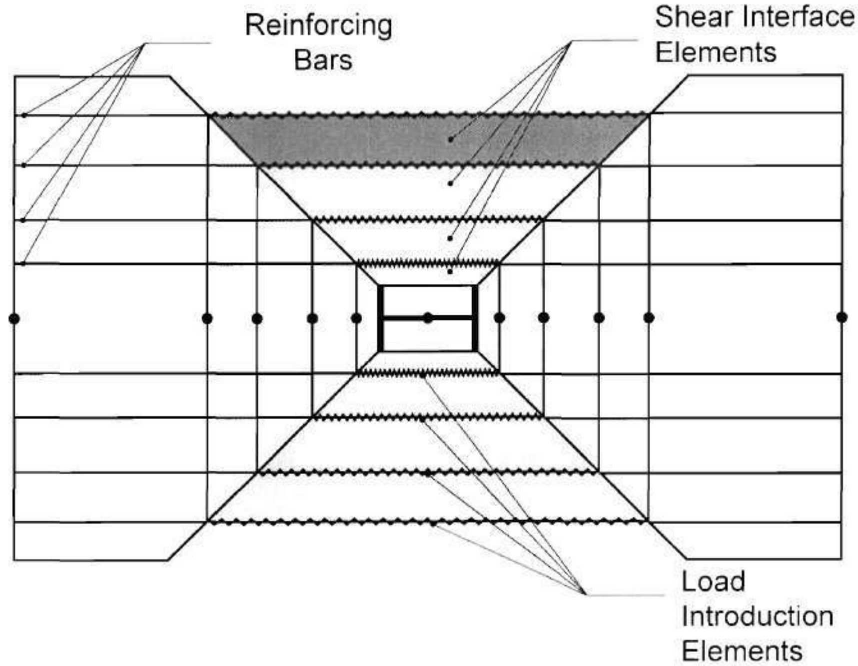


Figure 5. Slab force transfer mechanism

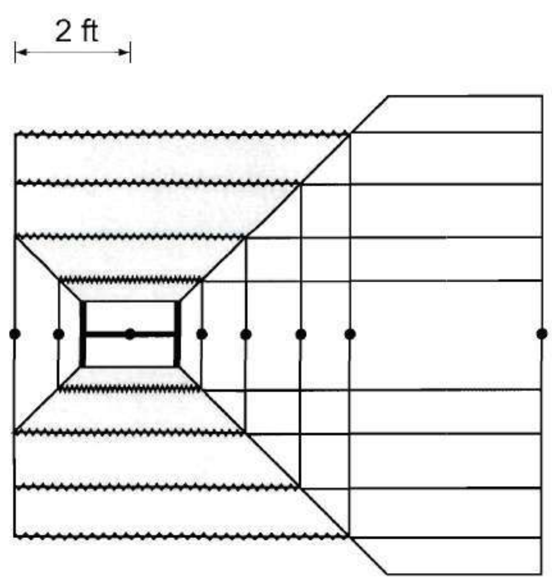
the column face and it is decreased linearly such that and at the full slab width, the concrete is assumed to be unconfined.

At the intersection of the longitudinal reinforcing bars with the tapered slab, we define a node where we exploit the assumption that plane sections remain plane across the tapered width of the slab within the beams. The longitudinal reinforcing bars are represented by load introduction elements that are composed of longitudinal steel bars in the slab and the tributary concrete slab area that is effective only under compression. The load introduction elements are attached to these nodes and they mainly transfer slab forces in tension and compression across the column line. In addition to these elements, a different set of elements is defined on each side of the column, called shear interface elements and they are tied to the nodes as shown in Fig. 6. Any relative movement between the nodes creates shear frictions in the concrete slab and developed forces in the slab are transferred into the inside of the column section profile.

In the experiment, the slab was extended 2 ft. beyond the centerline of exterior columns to provide anchorage for the continuous reinforcing bars in the slab. A similar model is used for the exterior part of the slab such that load introduction elements and shear interface elements are tied to the exterior nodes (Fig. 6b).



(a)



(b)

Figure 6. Analysis model (plan view of slab) (a) for interior column and,

(b) left exterior column.

The behavior in the vicinity of the beam-to-column connections is modeled by a component-based approach. That is, the force-deformation behavior of each of the structural components that provide the force transfer between the floor system and the steel column is modeled directly, and the different force-deformation models are combined to represent the complete behavior associated with this force transfer. The connection model is based on the work by Taylor (1999) and it is composed of seat angles, web angles and redirection springs that account for the contact between the slab and the column face. The seat angle is represented by a single component spring, which is in turn composed of four springs in parallel. These springs represent the effects of transverse column web load introduction, column flange bending, seat angle bending, and shear bolt slip and bearing.

A similar model is utilized for the lengths of the web angles tributary to each of the web angle-beam web and web angle-column flange bolts. The bearing between the slab and the column flanges is represented by "redirection springs" on each side of the column. The redirection springs are effectively gap elements, which have a large stiffness equal to the effective stiffness of the column web in transverse compression, but have zero stiffness when separation occurs between the column faces and the respective slab locations. The slab redirection spring, and the seat and web angle springs are all attached to plane section idealizations at the column flange faces (i.e., the sides of the panel zone) and at the cross-sections of the end of the beams, with the exception that slip is allowed between the slab and the steel beams.

The finite size and deformability of the column panel zone for strong-axis connections are modeled using a shear-panel constraint as shown in Fig. 7. This constraint idealizes the panel zone with rigid bars at its edges. Therefore, the rotations within the plane of strong-axis bending at the column faces on each side of the panel are assumed to be equal, and the in-plane rotations at the top and bottom of the panel, at the connection to the beam-column elements are assumed to be equal, but different than the column face rotations. Four degrees of freedom are defined at the panel zone element, which are horizontal and vertical degrees of freedom and rotational degrees of freedom, one corresponding to the rotation in the beam and one for the rotation in the column. Any difference between these rotations creates deformations in the panel zone.

The beam members are modeled using a partial composite beam element, and the columns are beam-column elements that have standard end displacement and rotational degrees of freedom. Both the partial-composite beam and the beam-column elements are distributed plasticity elements, and they are formulated using a mixed approach to alleviate the problems associated with over-constraint of the displacement fields in conventional displacement-based distributed plasticity elements (Alemdar 2001). The beam element has four degrees of freedom at each end, which are transverse and rotational degrees of freedom, and axial degrees of freedom at the reference axis of the steel beam and the concrete slab, It should be noted that any relative movement between axial degrees of freedom in the composite beam creates shear deformations in the stud shear connectors at the interface between the concrete slab and the steel beam. The deformability of stud shear connectors is explicitly included within the partial-composite beam element formulation in such a way that a continuous load-slip relationship is used to model this partial composite interaction. A fiber idealization of the slab and beam cross-sections is employed.

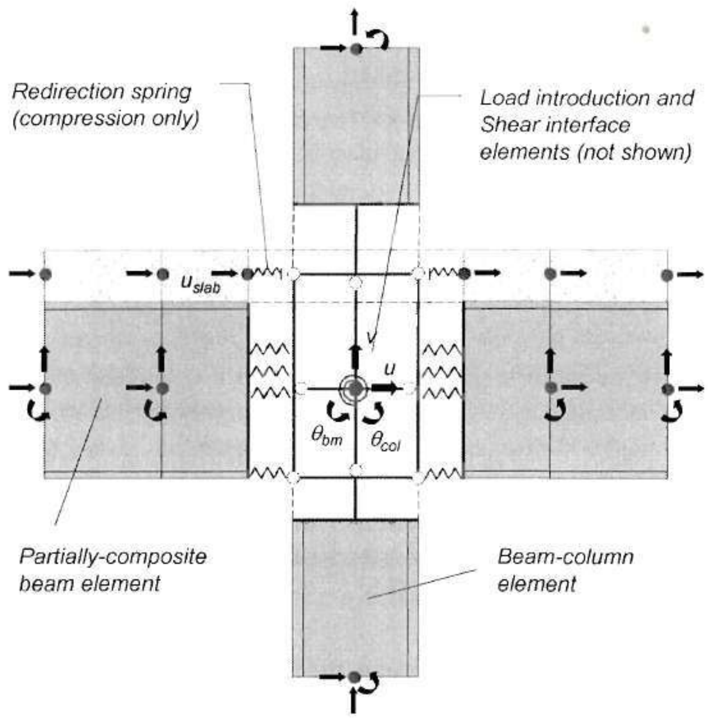


Figure 7. Analysis model (elevation)

The shear interface element is an isoparametric, inelastic, four-node plane stress element. Only shear deformations within this element are accounted for and the shear strength within this element is based on the shear-friction strength provisions in ACI-318-99. The model is assumed to be elastic-plastic with a strength of $0.2\,f_c^{'}$. Alternatively, the strength can be based on a direct concrete strut and tie idealization.

The hysteretic behavior of the various components in this study is represented by uniaxial models, which have the following attributes: (1) stable symmetric hysteretic behavior of panel zone elements, (2) gradual hardening in stiffness due to contact between connection angle components and the column flanges instead of abrupt stiffening of the force-deformation curve due to the contact as assumed in (White et al. 2000), (3) slip and bearing behavior of the shear bolts, (4) stiffness and strength degradation and pinching behavior in the slab concrete response and shear connectors, (5) cyclic hardening behavior of the web and seat angle components, and (6) cyclic hardening and Bauschinger effects of the steel beam fibers. Detailed descriptions of these uniaxial models are given in Taylor (1999).

Analysis Results

Experimental and current analysis results are first compared at the gravity load level of 15.8 kips. The moments at the connections recorded from the experiment are –883, -831, -751 and –803 k-in. from right to left. The corresponding values in the analyses are – 614, -740, -740, -614 k-in. The differences between these values can be attributed partly to the capability of the concrete to act in tension within the negative moment regions. The concrete model used in this study assumes that the concrete slab has no resistance in tension. Moreover, shrinkage deformations in the slab are not accounted for in this study. It is interesting to note that the exterior connection moments measured in the test are slightly larger than the corresponding interior connection moments.

The lateral load versus the story drift measured in the experiment is shown in Fig. 8 and the results of the current study are illustrated in Fig. 9. The current analysis predicts higher capacity both in positive and negative story drifts. It was reported in the experiment that at the end of the gravity loading there were small cracks in the slab at the column flange and that these cracks become more apparent at 0.75 percent drift. Furthermore, the final failure occurred at 1.5 percent drift by propagation of larger shear cracks from the tip of the column flange to the end of the slab at the left exterior column. In addition, the transverse bars at the exterior portion of the slab were also yielded. All these effects obviously caused a drop in stiffness and strength, which are not directly accounted for in the current study.

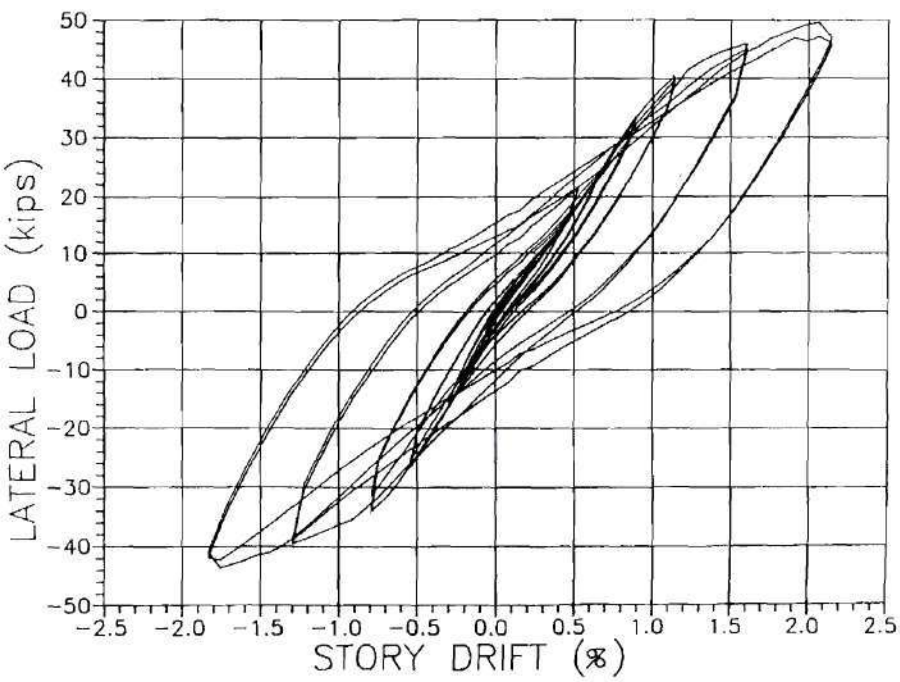


Figure 8. Applied lateral load versus story drift, experimental results

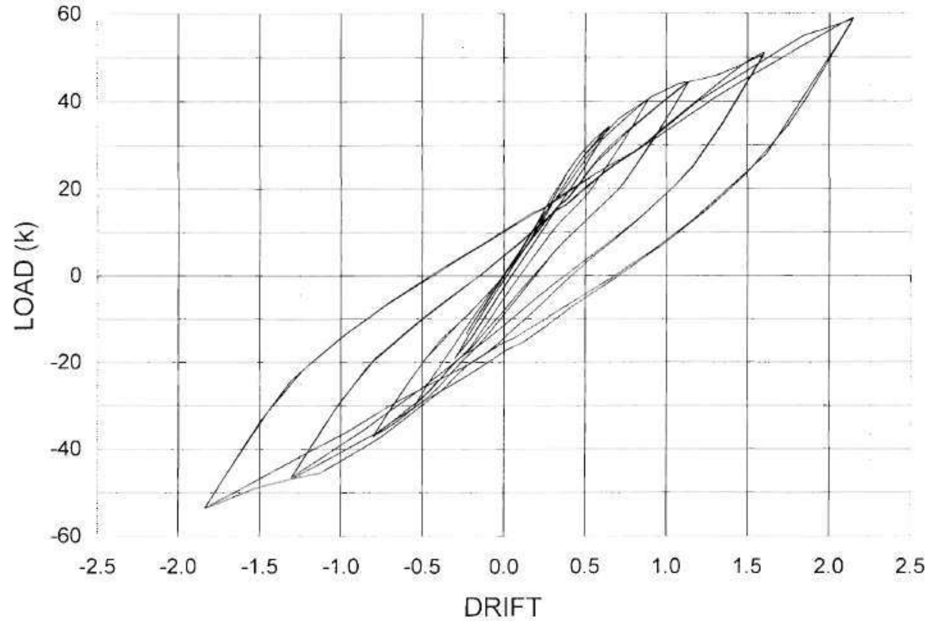


Figure 9. Applied lateral load versus story drift, analysis results

Figure 10 is the moment rotation curve for the right exterior connection recorded during the test. The analysis results for the same cyclic history are given in Fig, 11. It should be mentioned that when the connection moves from negative to positive bending, the seat angles come into contact with the column face, and thus the connection response stiffens gradually. Since the length of the connection angle that is in touch with the column face is changing under this loading, gradual changes in the stiffness are considered to account for this behavior. It is apparent from the figure that the connection model gives a larger moment capacity in negative bending than measured within the test while the rotations are in good agreement with the experimental results. In the analysis, it is noticed that the shear interface elements yield within the early cycles and two reinforcing bars at the interior column and eight reinforcing bars at the right exterior column are yielded at 2.15 percent drift. This causes a loss in stiffness when the connection reloads in negative bending from large positive rotations. The prediction of the connection response for positive bending is better than negative bending.

The force-deformation response of the left-side seat angle assembly of the interior joint is illustrated in Fig. 12. It can be observed from the figure that bolt slip and bearing deformations are relatively small as reported in the test. The bolts slip into bearing at a load of 108 kips. The interior panel zone exhibits yielding at 169 kips shear force (see Fig. 12).

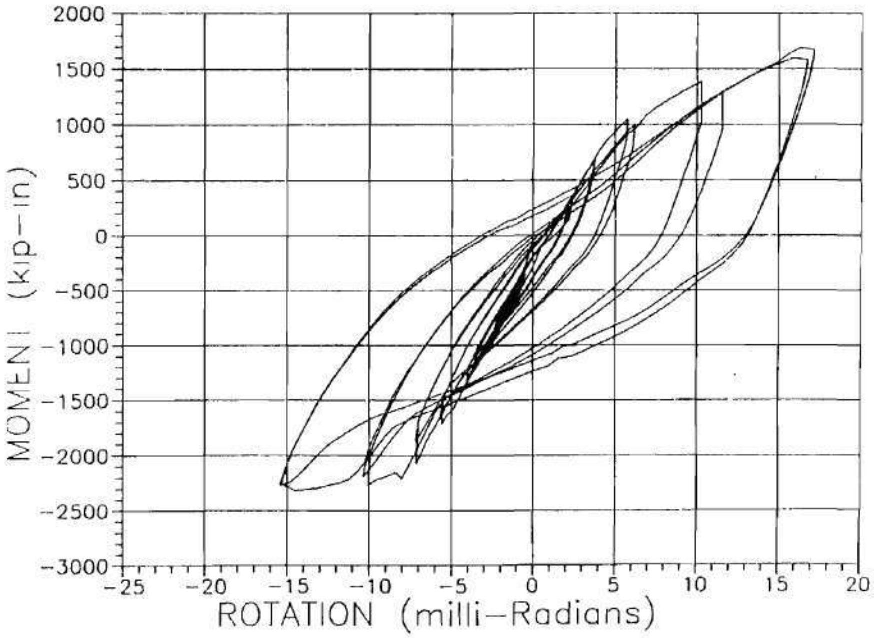


Figure 10. The moment-rotation curve for the right exterior connection, experimental results

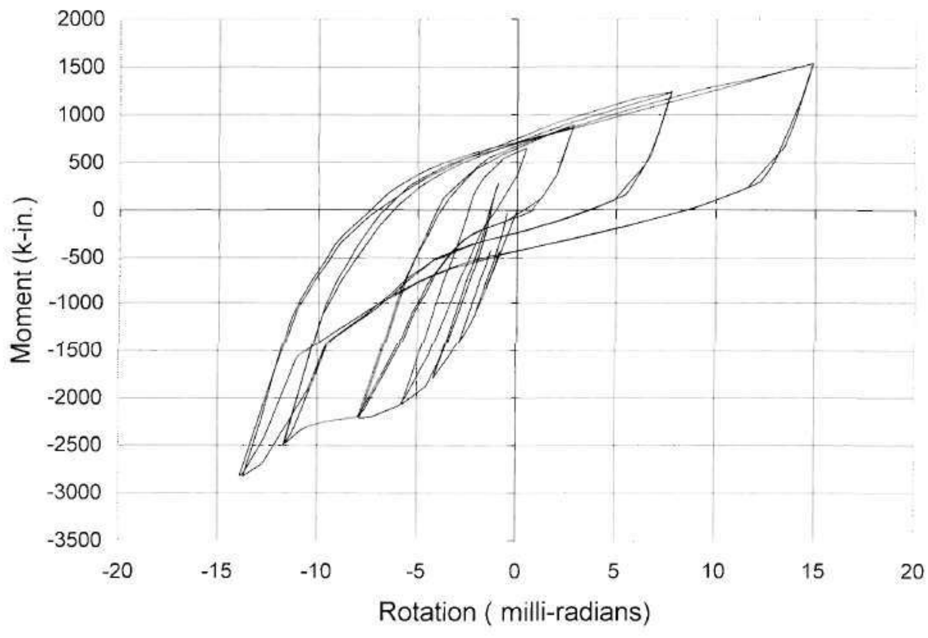


Figure 11. Analysis results for the moment-rotation of the right exterior connection

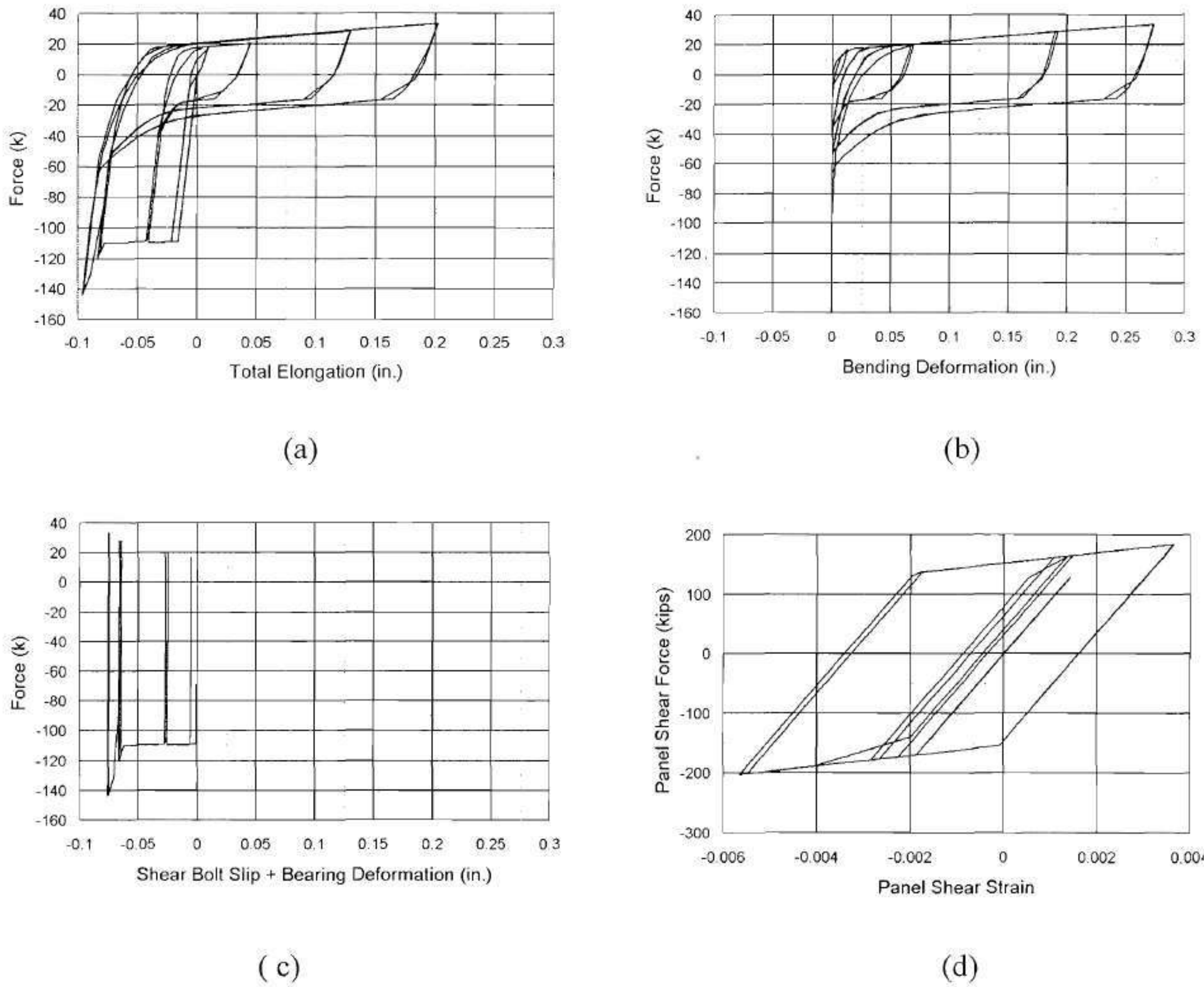


Figure 12. Force-deformation response of left-side seat angle assembly and force-deformation response of the panel zone of the interior joint

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